Low Energy Evaporative Cooling System Linked With Ground Water For Hot And Dry Climate

Kumara Vamsi Krishna Vandanapu[1], Vijay B Mohan[2], Ajay Kumar Yadav[3]

[1] Hochschule Nordhausen, Germany

[2] Technical University of Munich, Germany

[3] National Institute of Technology Karnataka, India

Abstract

In this study, we investigate energy and exergy analyses of indirect evaporative cooling system linked with ground water for different ambient conditions and compare it with conventional evaporative cooler. Further the advantage of using ground water is justified by comparative study between ground water and normal water based evaporative cooling system. In order to compare ground water and normal water based evaporative cooling system, average ambient temperature and relative humidity variation of Ahmedabad (INDIA) is considered. A simulation program using MATLAB is developed to simulate and evaluate the evaporative cooling system. According to the simulation results obtained for ground water based evaporative cooler, energy efficiency (COP) is found to be between 10.97 and 21.43 while exergetic efficiency (2nd law efficiency) is found to be between 75% and 61% for constant ambient conditions. The results show that with increase in ambient temperature COP reduces, and irreversibility is found to be more in the case of conventional evaporative cooler. Even though irreversibility is obtained to be nearly same for both normal water and ground water linked evaporative cooling system, COP of the ground water-based system is confirmed to be higher at higher ambient temperature since ground water temperature is invariant.

Nomenclature

C	Specific heat capacity, $kJkg^{-1}K^{-1}$
D	Diameter of the tube, mm
dp	Total pressure drop, Pa
E	Total energy supplied, $kJkg^{-1}$
EC	Evaporative cooler
f	Friction factor
H	Pressure head, m
h	Specific enthalpy, $kJkg^{-1}$
HX	Heat exchanger
I	Irreversibility (Exergy destroyed) kW
m	Mass flow rate kgs^{-1}
N	No of transfer units
P	Pressure, Pa
Re	Reynolds number
s	Specific entropy $kJkg^{-1}$
S	Entropy kJ
T	Temperature, °C
V	Velocity, m/s
v	Specific volume, m^3kg^{-1}
X	Correction factor

Symbols

ε	Effectiveness
$\eta 1$	Coefficient of performance
$\eta 2$	Second law efficiency (Exergetic eff.)
ω	Specific humidity
ϕ	Relative humidity

Subscripts and Superscripts

1	Ambient conditions
2	Exit of heat exchanger
3	Exit of evaporative cooler
4	Exit of room
i	Inlet
o	Outlet
hx	Heat exchanger
w	Water
g	vapor
d	Dry air
gen	Generated
ec	Evaporative cooler
a	Ambient

1. Introduction

Due to environmental problems caused by synthetic refrigerants, there has been an upswing in the use of eco-friendly air conditioning system. Even though the air conditioning systems which make use of synthetic refrigerants are able to maintain comfort conditions (29 °C and 60% RH) with relative ease, the ill effects on the environment cannot be ignored. The search for self-sustained eco-friendly air conditioning system takes us back to the concept of evaporative cooling. Evaporative cooling is one of the oldest forms of climate control still found today. It is very effective and efficient for hot and dry climate. The potential of cooling of these systems mainly depends on the wet bulb temperature of the ambient environment, hence for higher ambient temperatures, cooling effect produced will be lower with less comfort due to relative humidity being more than 60%. In order to reduce the wet bulb temperature of the ambient air artificially, many attempts have been made in the past using cool water to remove sensible heat of ambient air. But the temperature of water will be dependent on outdoor (OD) air conditions and it is difficult to obtain cool water at around 23 °C in summer (hot and dry weather). The use of ground water as the cold fluid in heat exchanger can serve as a solution to the problem. The use of ground water over normal water can be justified on the fact that the temperature of ground water ~23°C is invariant with atmospheric conditions [2]. Making use of heat exchanger with ground water as the cold fluid, sensible cooling of ambient air is performed followed by conventional evaporative cooling. Since the potential of cooling depends on the wet bulb temperature of the air entering the evaporative cooler, comfort conditions are satisfied (29°C and 60% RH) in the new system. The input energy required for this system is met with photo voltaic cells, enabling this a self-sustained environmental friendly device. Another advantage of ground water based system is to get heating effect during winter. There have been many attempts in the past to analyse the thermodynamic processes involved in an indirect evaporative cooling system (IDEC). Analysis of IDEC system based on dew point for buildings was performed by Xudor and Duan [1]. Performance enhancement study of an IDEC using geothermal energy was carried out by Issam and Hind [2] in which well water was used as a cold fluid to regulate the temperature of a greenhouse. Shahab Moshari [3] performed an analytical study to determine the pressure drop involved in an IDEC for power reduction.

In order to check the viability of the new system a thorough thermodynamic study needs to be performed considering the irreversibility in each device [4]. Second law analysis of ground coupled heat pump system [5,6] gives us basic idea to employ the same method for any air conditioning system. The second law analysis of a thermal system provides us invaluable insight into the operation of the system. It is a powerful tool in the design, optimisation and performance evaluation of energy systems [7-9]. This analysis can be used to identify the main sources of exergy destruction and to minimise the generation of entropy in a given process where the transfer of energy and material takes place [10,11]. With the available literature, it can be seen that a comprehensive study on IDEC system linked with ground water is not found.

In this study, a step by step algorithm is developed in MATLAB in order to evaluate the variation in coefficient of performance and second law efficiency of the new system with changes in ambient conditions. In order to make the study more practical, temperature and relative humidity variation of Ahmedabad is considered from February to May. The credibility of the new system is further strengthened by comparison study with conventional evaporative cooler and with same system which uses normal water as the cold fluid.

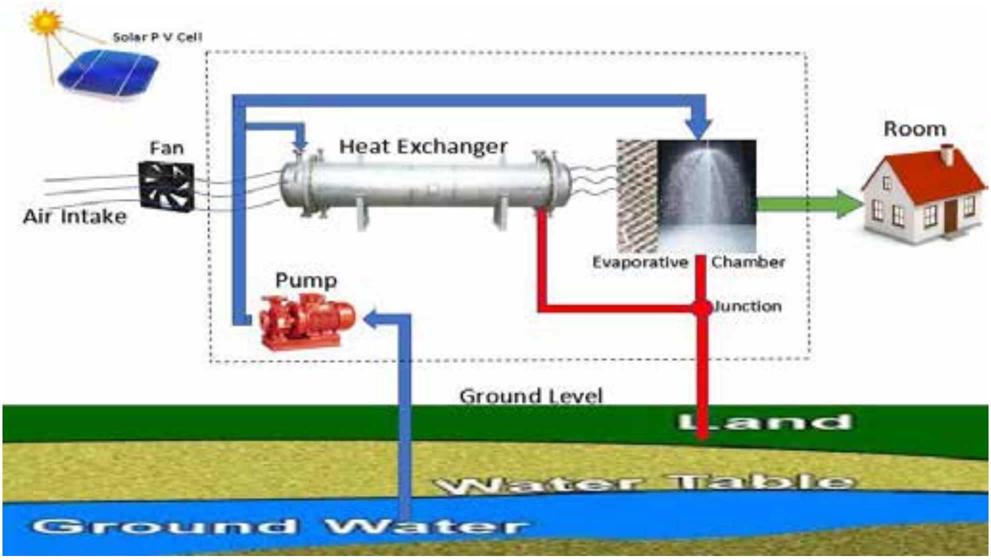

Figure 1. Schematic diagram of ground water linked evaporative cooling system

Description of schematic of proposed air conditioning system

The schematic of the proposed air conditioning system for cooling of a small room is illustrated in Figure 1. The schematic mainly consists of 5 components i.e., Solar Photovoltaic (PV) cell, water Pump, Heat exchanger, Evaporative cooler and Blower. PV cell is used to supply power to blowers and pump to make the system self-sustained. Pump is used to draw water from the ground and to circulate in the system. Blowers are used to maintain the required mass flow rate of air in the system and in the room to provide the required cooling effect. An optimised heat exchanger whose specifications based on effectiveness method must be selected to exchange heat with ambient air using ground water as the cold fluid. A cross flow heat exchanger is chosen with ground water made to circulate in the tubes and ambient air passing over them. The cooled air obtained from heat exchanger is made to undergo cooling and humidification process in the evaporative cooler with the required flow of ground water.

2. Thermodynamic analysis

The assumptions made in the analysis presented in this study are

1. All processes are assumed to be steady.
2. Air is considered as an ideal gas with a constant specific heat.
3. Heat exchanger and evaporative cooler is modelled as a steady flow device for entropy balance.
4. Frictional loss through pipes in heat exchanger is ignored.
5. The process in the humidifier is assumed to be adiabatic saturation process. Mass flow rate of make-up water in evaporative cooler is hundred times more than the water lost in humidification process.
6. Ground water is at a depth of 10 m below the ground level.

Operating parameters of the ground water-based system is given in Table 1

Table 1. Operating parameters

Operating parameter	Value
Ambient temperature	33-42°C
Ambient relative humidity	20-35%
Room temperature	29°C
Room relative humidity	60%
Ground water temperature Cooling load	20°C 3.5 kW
Effectiveness of HX, ε_{hx}	0.9
Effectiveness of Evaporative cooler, ε_{ec}	0.9
Mass flow rate of water in heat exchanger	1 kg/s

Energy and entropy balances

The governing equations for mass and energy balance in a steady flow process are given by

$$\sum \mathrm{m_i} = \sum \mathrm{m_0} \quad (1)$$

$$\sum E_i = \sum E_0 \quad (2)$$

Entropy balance in heat exchanger can be expressed as,

$$\mathrm{s_i^{hx}} = \mathrm{s_i^d} + \omega_1 \times \mathrm{s_i^g} \quad (3)$$

$$\mathrm{s_0^{hx}} = \mathrm{s_o^d} + \omega_1 \times \mathrm{s_o^g} \quad (4)$$

$$\mathrm{S_{gen}^{hx}} = \mathrm{m_d}\left(\mathrm{s_0^{hx}} - \mathrm{s_i^{hx}}\right) + \left(\mathrm{s_0^w} - \mathrm{s_i^w}\right) \quad (5)$$

where $\mathrm{S_{gen}^{hx}}$ represents the entropy generated in the heat exchanger. Entropy balance in evaporative cooler can be expressed as,

$$\mathrm{s_i^{ec}} = \mathrm{s_i^d} + \omega_2 \times \mathrm{s_i^g} \quad (6)$$

$$\mathrm{s_0^{ec}} = \mathrm{s_o^d} + \omega_3 \times \mathrm{s_o^g} \quad (7)$$

$$\mathrm{S_{gen}^{ec}} = \mathrm{m_d}\left(\mathrm{s_0^{ec}} - \mathrm{s_i^{ec}}\right) + \left(\mathrm{s_0^w} - \mathrm{s_i^w}\right) \quad (8)$$

where $\mathrm{S_{gen}^{ec}}$ represents the entropy generated in the evaporative cooler. Irreversibility in the system can be expressed as

$$\mathrm{I} = (\mathrm{t^0} + 273.15) \times (\mathrm{S_{gen}^{hx}} + \mathrm{S_{gen}^{ec}}) \quad (9)$$

Where, $\mathrm{t^0}$ is known as the reference temperature. For calculation purposes, atmospheric conditions (1 atm and 25°C) can be considered as reference environment. But in case of systems which make use of air and water at atmospheric conditions reference temperature is taken as the lower of the average temperature for air and water. [12]

Coefficient of performance and second law efficiency

Coefficient of performance of the system can be expressed as

$$\eta 1 = \frac{\text{Cooling load}}{\text{Energy supplied}} \quad (10)$$

Exergetic efficiency of the system can be expressed as

$$\eta 2 = \frac{\text{Exergy supplied}}{\text{Exergy supplied+Irreversibility}} \quad (11)$$

Estimation of power consumption

Total power consumption is the sum of fan and pump power.

$$\text{Fan power} = m_d \times v_d \times dp \quad (12)$$
$$\text{Pump power} = m_w \times v_w \times \rho \times g \times H \quad (13)$$

Based on effectiveness method a cross flow heat exchanger with 4×8 tubes of diameter 20 mm and pitch of 30 mm was considered with aligned configuration. Area of heat transfer was obtained from Eqn (14)

$$\varepsilon_{hx} = 1 - e^{\frac{e}{G \times n}(-N \times G \times n) - 1)} \quad (14)$$

Where, $n = N^{-0.22}$ and G is the ratio of specific heats. By knowing the specifications of heat exchanger pressure drop in the heat exchanger was obtained from Eqn (15,16)

$$\frac{1}{\sqrt{f}} = -2 \ln[\frac{e}{3.7D} + \frac{2.51}{Re\sqrt{f}}] \quad (15)$$

$$dp_{hx} = \text{no of tubes in each row} \times X \left(\frac{\rho \times V_{max}^2}{2}\right) f \quad (16)$$

Eqn (15) is known as the Colebrook equation. Using the theory of Shahab [3], pressure drop in evaporative cooler is assumed to be three times the pressure drop in heat exchanger. From the total pressure drop obtained from Eqn (17), fan power consumption was calculated.

$$dp = 4 \times dp_{hx} \quad (17)$$

All the data required for heat exchanger analysis was taken from Incropera [17]. Psychrometric data was taken from PK Nag [15], CP Arora [16] and refprop software [14].

Estimation of thermodynamic properties of moist air at different states

Steps followed to obtain thermodynamic properties of moist air are given below: Saturation pressure at ambient and room conditions are found by using the correlation given by

$$P_s = 610.78 \times exp(\frac{t}{t+238.3} \times 17.2694) \quad (18)$$

Specific humidity at ambient and room conditions can be found by first finding partial pressure of water at each state using Eqn (19) and then using the result in Eqn (20).

$$P_w = \phi \times P_s \tag{19}$$
$$\omega = 0.622 \times \frac{P_w}{P_a - P_w} \tag{20}$$

Wet bulb temperature at any state can be found by making use of Eqn (18) and guessing the value of wet bulb temperature such that Eqn (21) is satisfied.

$$P_s = P_{wbt} - (1.8 \times \frac{P_a(t - t_{wbt})}{2700}) \tag{21}$$

Where, P_{wbt} is the saturation pressure corresponding to wet bulb temperature and t_{wbt} is the wet bulb temperature.Specific enthalpies of humid air at any state is found by Eqn (17) by knowing the specific humidity and temperature

$$h = C_d \times t + \omega(2500 + 1.88 \times t) \tag{22}$$

Specific humidity doesn't change in the heat exchanger and remains the same as ambient conditions but decrease in dry bulb temperature of air is obtained by Eqn (23).

$$\varepsilon_{hx} = \frac{(t_1 - t_2)}{(t_1 - t_w)} \tag{23}$$

Dry bulb temperature of humid air at the exit of evaporative cooler is found by using Eqn (24)

$$\varepsilon_{Ct} = \frac{(t_2 - t_3)}{(t_2 - t_{wbt})} \tag{24}$$

Where, T_{wbt} is the wet bulb temperature corresponding to dry bulb temperature of humid air at the exit of heat exchanger.
Applying energy balance across the evaporative cooler and noting that specific enthalpy of humid air remains constant throughout the adiabatic saturation process specific humidity at the exit of evaporative cooler is found out by Eqn (25)

$$\omega_3 = \frac{h_2 - C_d \times t_3}{2500 + 1.88 \times t_3} \tag{25}$$

By knowing specific humidity and dry bulb temperature of humid air, specific enthalpy can be found at all states from Eqn (22). Required mass flow rate that is to be maintained by the blowers is found from Eq. (26)

$$m_d = \frac{\text{Cooling load}}{h_4 - h_2} \tag{26}$$

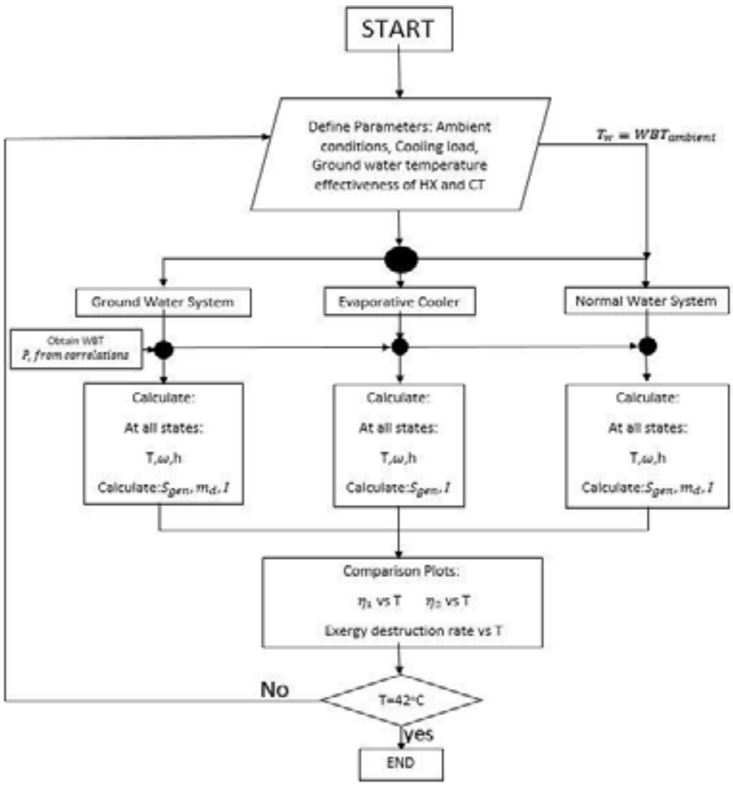

Figure 2. Flow chart representing the developed code for comparison study

3. Results and Discussion

In order to evaluate the performance of the proposed system in the summer season, Ahmedabad (India) weather condition is considered. Variation of temperature and relative humidity of Ahmedabad during summer is shown in Figure 3 [13].

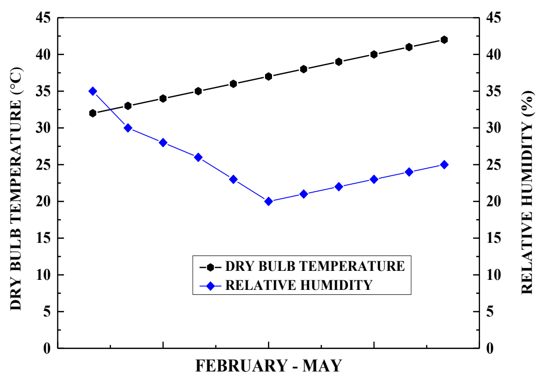

Figure 3. Variation of outdoor air properties during summer at Ahmedabad

Comparison at Constant Ambient Conditions

The first comparative study of the three systems is made at a particular dry bulb temperature (39°C) and relative humidity (22%) by indicating the thermodynamic process undergone by humid air on a psychrometric chart as shown in Figure 4.

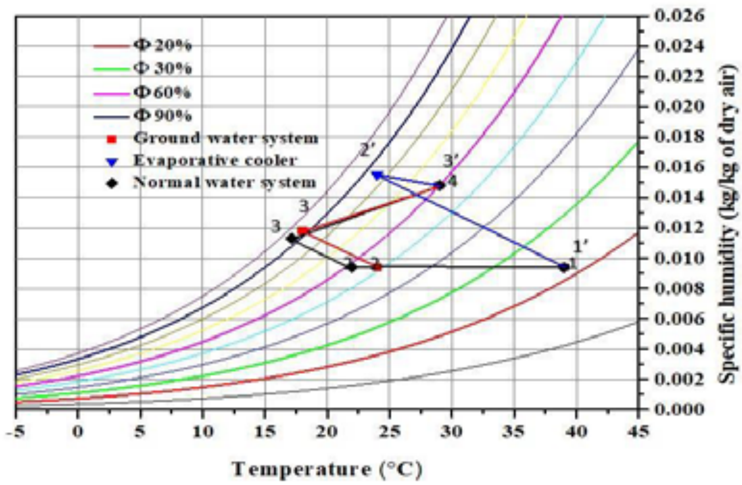

Figure 4. Thermodynamic process on a psychrometric chart

As indicated in the figure 4 relative humidity at the exit of evaporative cooler in the case of conventional evaporative cooler is much higher than the comfort conditions (60%). Hence, required mass flow rate and energy input is highest compared to other systems. Sensible cooling obtained from ground water is higher than normal water which results in lower gain in specific humidity inside the evaporative cooler. Exergy analysis at chosen OD condition is carried out for all the systems and results are shown in Table 2. It is clear from the table that ground water-based system has higher COP and lower rate of exergy destruction. Since rate of entropy increase in a phase change process is considerably higher than sensible heat transfer, ground water coupled evaporative cooling system has the least entropy increase. Further, lesser mass flow rate of air implies lower requirement of energy supplied to the blower.

Table 2. Comparison of performance parameters

Parameter	**Ground water system**	**Normal water system**	**Evaporative cooler**
Room conditions	29°C and ϕ 60%	29°C and ϕ 60%	29°C and ϕ 60%
Required mass flow rate	0.17 kg/s	0.29 kg	0.96 kg/s
COP	22.7	20.3	13.3
Exergy destruction (HX)	0.11 kW	0.1 kW	--------
Exergy destruction (EC)	0.43 kW	0.56 kW	1.03 kW
Second law efficiency	0.52	0.49	0.20

By extending the same study at higher outdoor temperatures (above 40°C) it is found that evaporative cooler cannot produce necessary cooling effect to maintain comfort conditions while ground water-based system satisfies comfort condition at lowest mass flow rate and exergy destruction. The theoretical results obtained for a particular ambient condition suggest that ground water coupled evaporative cooling system is much more efficient than the other two cooling systems. But in order to verify the new system's reliability and sensitiveness to operate efficiently at varying ambient conditions, it is necessary to evaluate its performance during the entire summer season.

Comparative Study Throughout the Summer Season

Comparative Study of Rate of Exergy Destruction in HX and EC

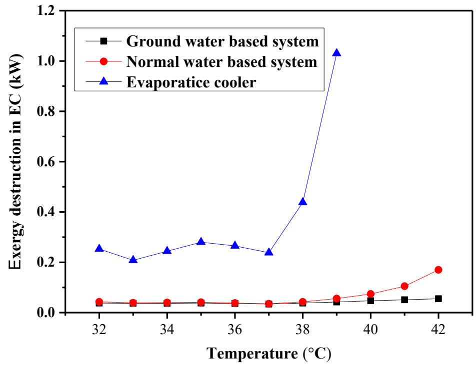

Figure 5. Variation of exergy destruction with outdoor conditions in ec

Figure 5 and 6 represents the variation of exergy destruction in HX and EC of all three systems with outdoor conditions. It is clear from Figure 8 that exergy destruction of HX in both ground and normal water systems varies only at higher outdoor temperatures since temperature difference between ground water and OD air increases. Figure 7 indicates that exergy destruction in conventional evaporative cooler is the highest due to significant gain in specific humidity. Exergy destruction of EC in ground water-based system is lower than normal water-based system at higher OD temperatures due to increase in sensible cooling in the ground water-based system. Total exergy destruction in ground water-based system is lowest at all outdoor conditions because increase in exergy destruction in EC of normal water-based system is more than the increase in exergy destruction in HX of ground water-based system.

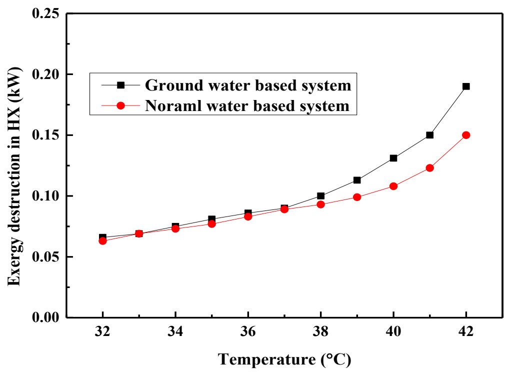

Figure 6. Variation of exergy destruction with outdoor conditions in hx

Comparative Study of COP and Exergetic Efficiency

The final comparative study of the three systems is performed throughout the summer season for Ahmedabad weather. Figure 7 illustrates the variation of COP with OUTDOOR conditions for all three cooling systems. Comparative study between the three systems was performed at fixed cooling load of 1 TR. COP of evaporative cooler is significantly higher than the ground and normal water-based system due to lower requirement of energy supplied and increase in latent heat load with decrease in OD air temperature. But at temperatures above 40°C, COP of evaporative cooler becomes negative indicating the incapability to maintain required cooling effect. COP of both the ground and normal water-based systems is found to be nearly same at lower outdoor temperature but at higher outdoor temperature COP of normal water-based system decreased significantly. Lower value of COP of normal water-based system at higher outdoor temperature occurs due to increase in temperature of normal water while ground water remains invariant with change in outdoor temperature.

Figure 8 illustrates the variation of exergetic efficiency with outdoor conditions for all three systems. Comparative study is performed by fixing the cooling load as constant at all conditions. Due to large amount of specific humidity gain in conventional evaporative cooler when compared to IDEC (ground and normal water system), exergetic efficiency of evaporative cooler is significantly lower. Exergetic efficiency of ground and normal water system remains same at lower outdoor temperatures, but ground water system is found to have higher value of exergetic efficiency at higher outdoor temperatures due to increase in sensible cooling obtained in the heat exchanger.

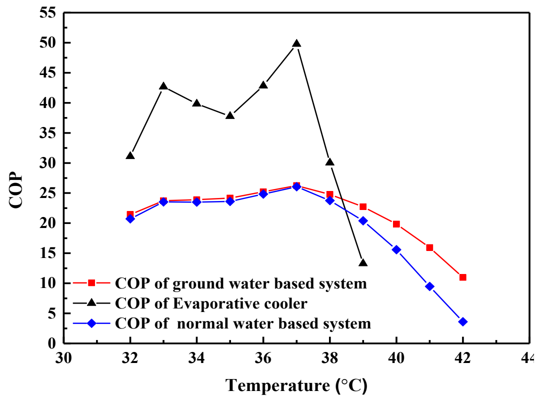

Figure 7. Cop variation with outdoor conditions

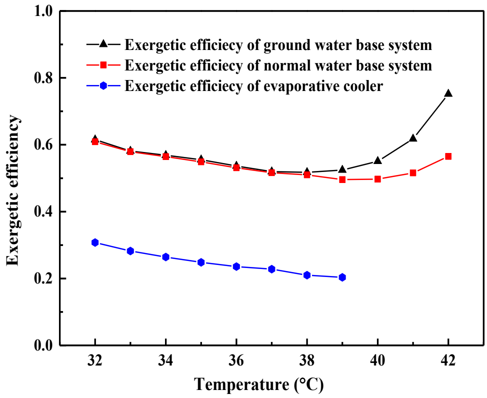

Figure 8. Exergetic efficiency variation with outdoor conditions

4. Conclusion

The main aim of this study is to develop a self-sustainable, eco-friendly, efficient alternative to conventional vapor compression refrigeration system for room air conditioner. The proposed ground water based evaporative cooling system is found to maintain comfort conditions better with varying ambient conditions. Hence, it can be concluded that the proposed system is more reliable and sensitive to cooling load changes than the evaporative cooler. Use of ground water over normal water can be justified from the fact that ground water temperature is invariant of ambient conditions while that of normal water depends on it. This is the main reason for COP of normal water-based system being significantly lower at higher outdoor temperature.

This study is concerned with the development of a cooling system which can operate only in hot and dry climate. In order to extend the cooling system to humid climates dehumidification of air is necessary. Hence a regenerative desiccant wheel coupled with the ground water system can serve the purpose. Further the same system (without evaporation) can be extended to winter climate by taking the advantage of ground water as a heating fluid.

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